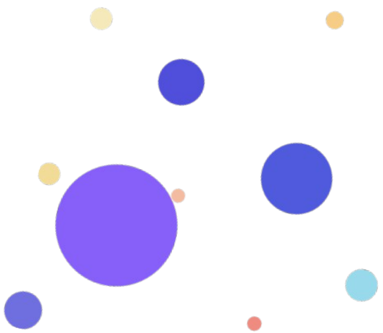
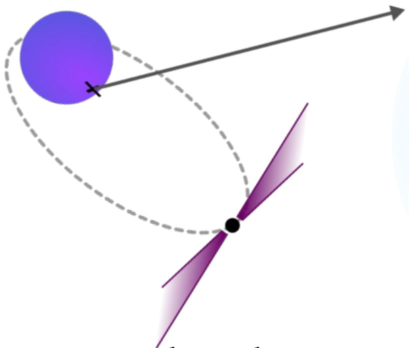
Labex UnivEarthS
Université Paris Cité

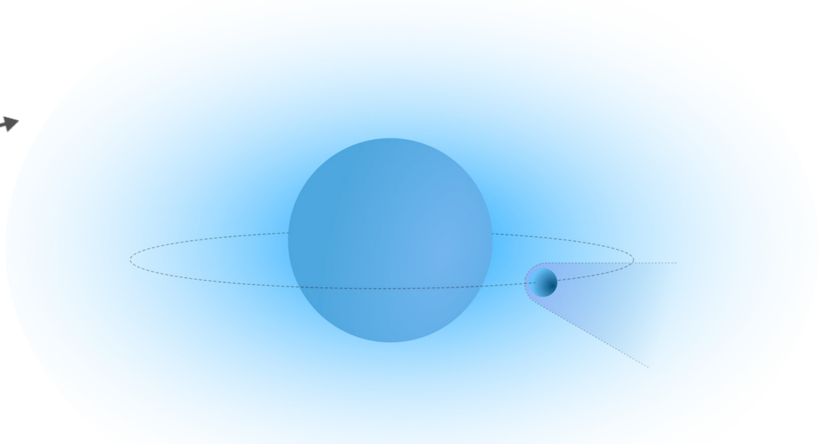
Observing the history of binary star systems



Formation



Natal Kick



X-ray phase

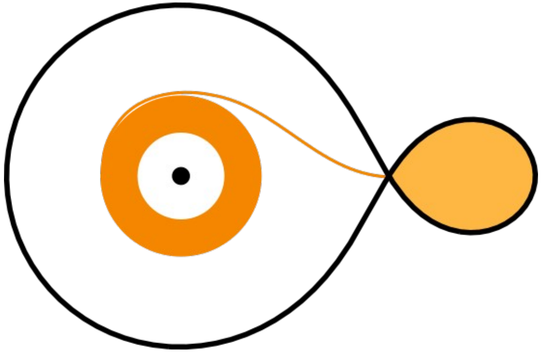
Francis Fortin – Postdoc LabEx UnivEarthS – APC

X-ray binaries cheat sheet

- Discovered in the 1960’
- Hard X-ray emission powered by accretion
- Transient or persistent
- Disks, jets, stellar winds…

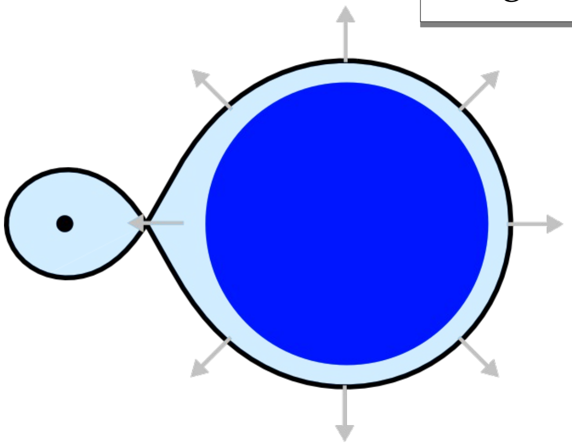
Companion star: low mass (< 1 $M_\odot$) or high mass (> 8 $M_\odot$)

Low Mass X-ray Binaries

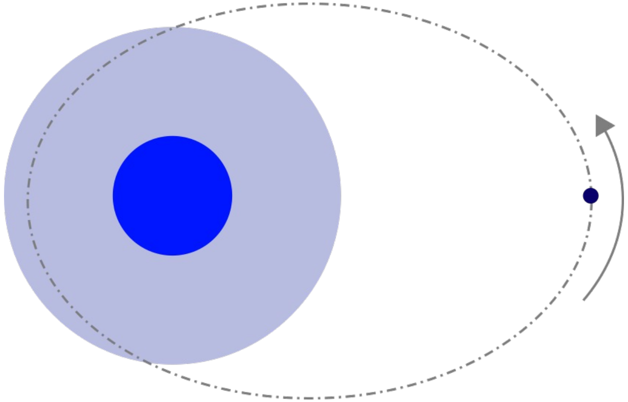


Roche lobe overflow

High Mass X-ray Binaries



Wind accretion



Decretion disk

Evolution of High-Mass X-ray Binaries (HMXBs)

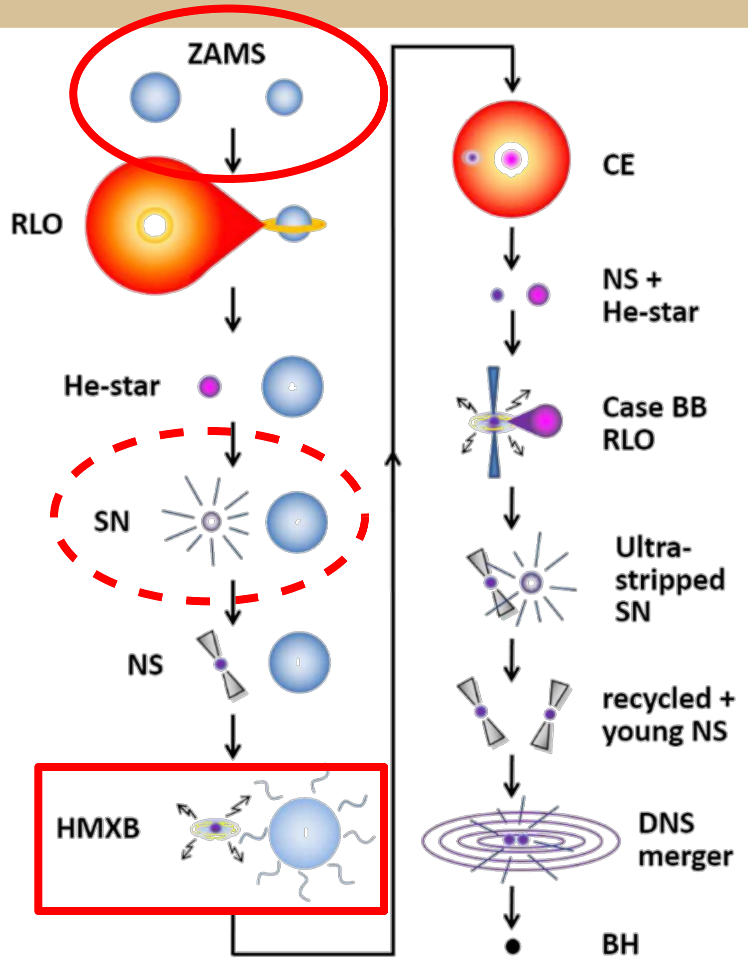
- X-ray systems : just a phase in the life of a binary

Preceded by :

- supernova event
- initial mass transfer

Followed by :

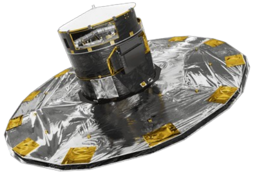
- common envelope
- mass transfer
- another supernova
- final compact merger



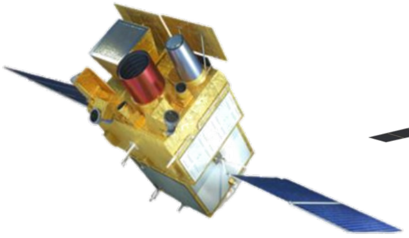
Tauris+2017

Observational prospects


VLT

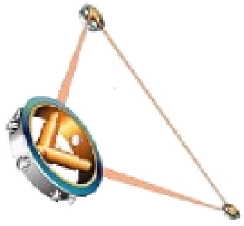

Gaia

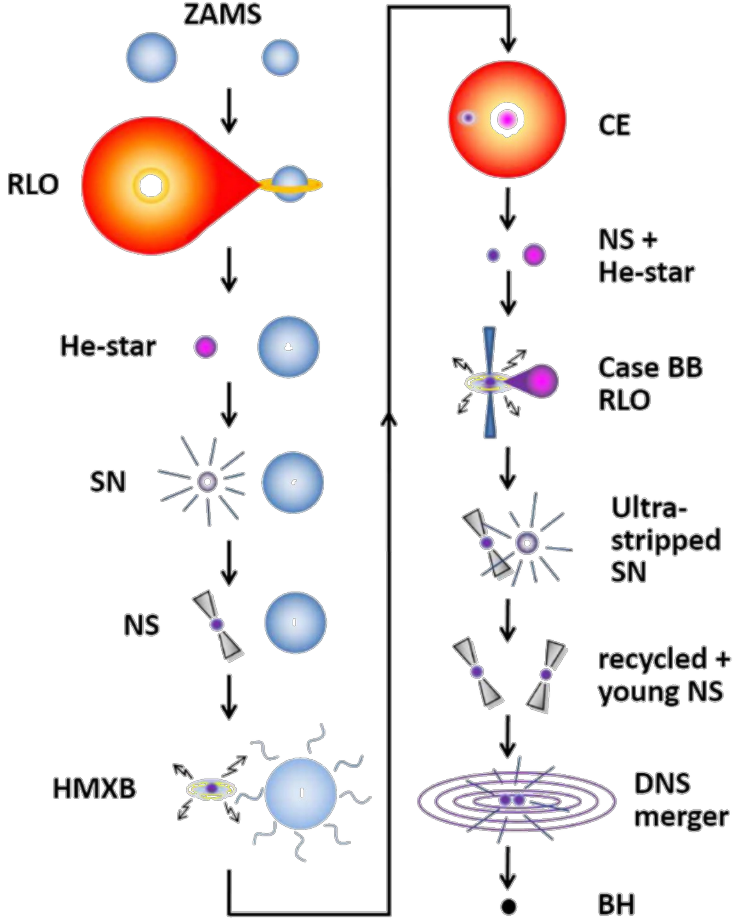

LSST


SVOM


Athena


LIGO / Virgo / KAGRA

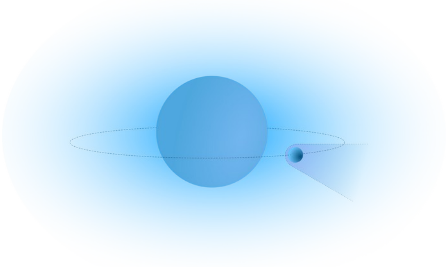

LISA



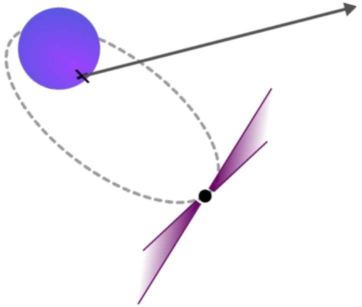
Tauris+2017

Observing the history of binary star systems

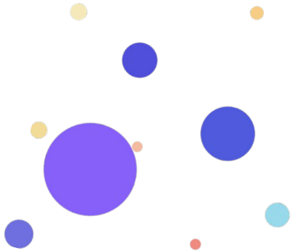
I – The most obscured supergiant HMXB in the Galaxy



II – Impact of the natal kick in binaries

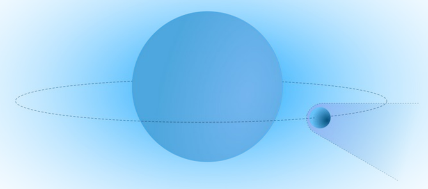


III – Finding the birthplace of stellar systems



Most Obscured System Since 2002™

IGR J16318-4848: the first source detected by *INTEGRAL* Walter+2003



X-rays: $N_H = 0.9 – 2 \times 10^{24}\ cm^{-2}$

(*ASCA*, 2-10 keV, Revnivtsev+2003, *XMM-Newton*, 0.3 – 13 keV, Matt & Guainazzi 2003, *INTEGRAL*, 5-13 keV, Walter+2003)

Optical / IR: $A_V = 18.3 +/- 0.4$ mag

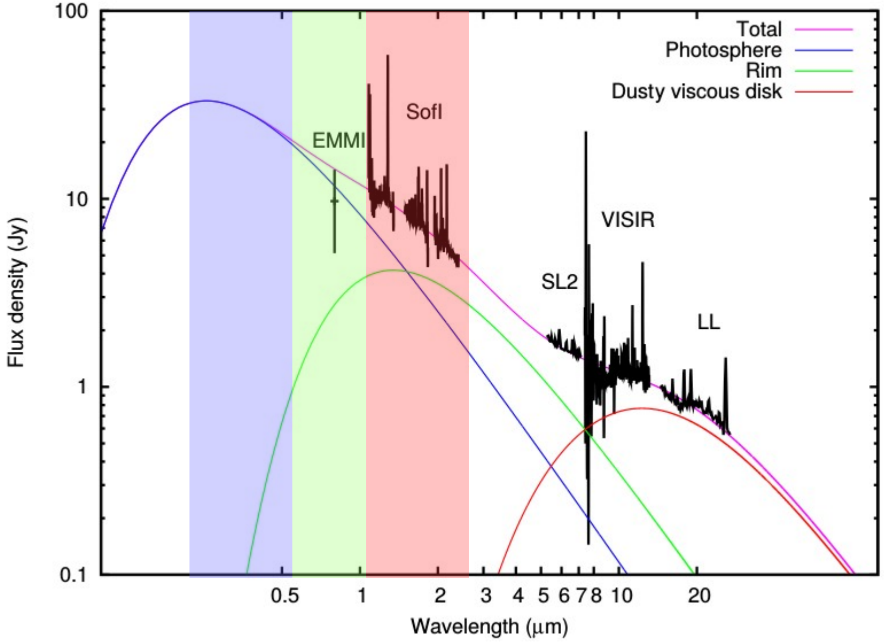
(VISIR, Spitzer & SofI, Chaty & Rahoui 2012)

X-ray absorption = 100x optical → opaque material near accretor ?

A complex environment

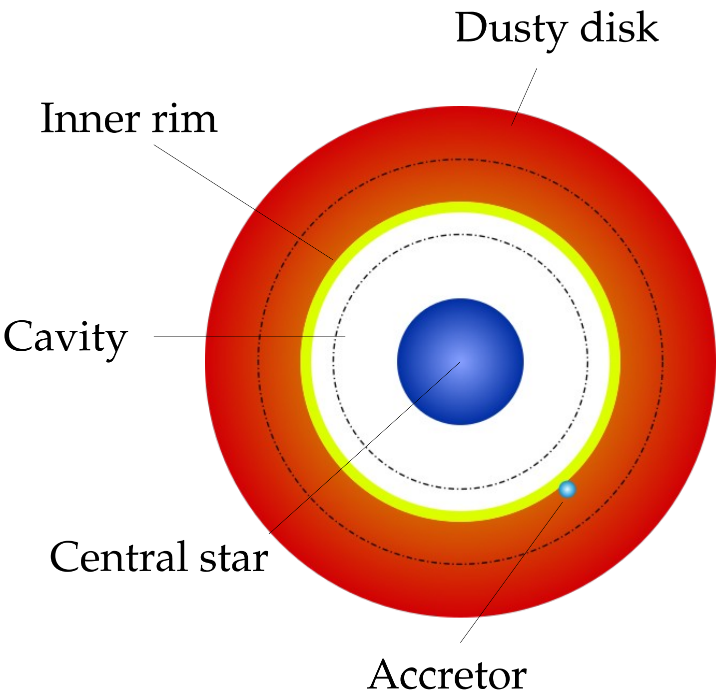
IGR J16318-4848

Broadband spectrum

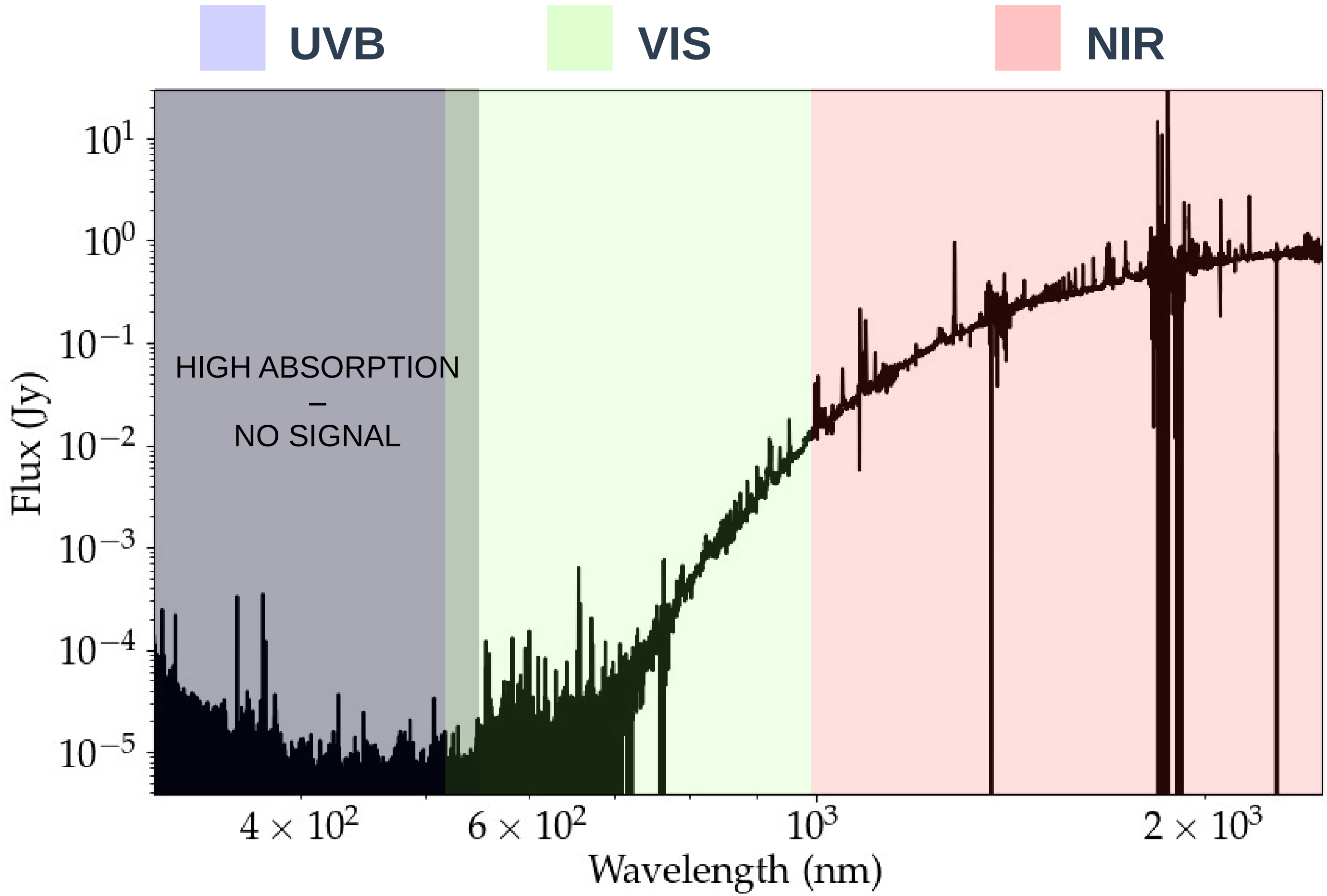


Chaty & Rahoui 2012

Pole-on view

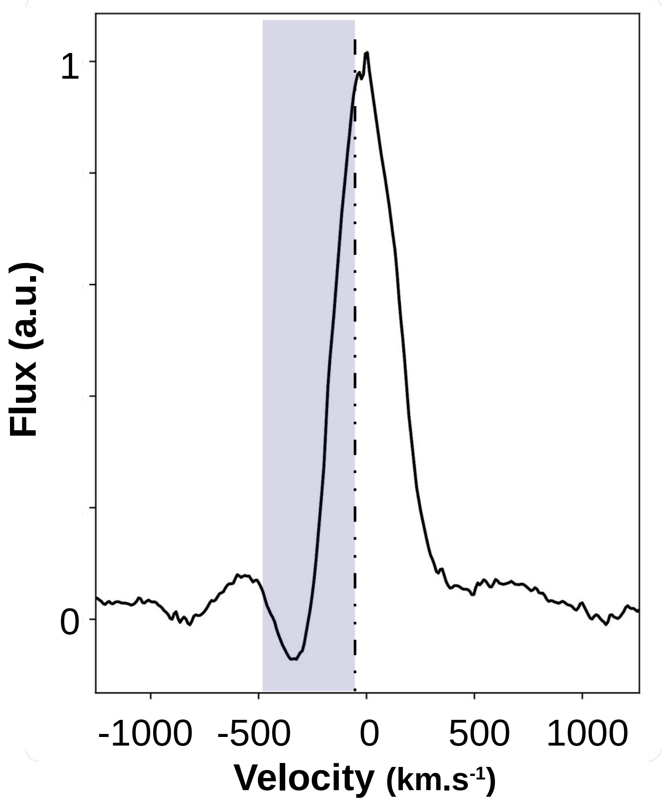


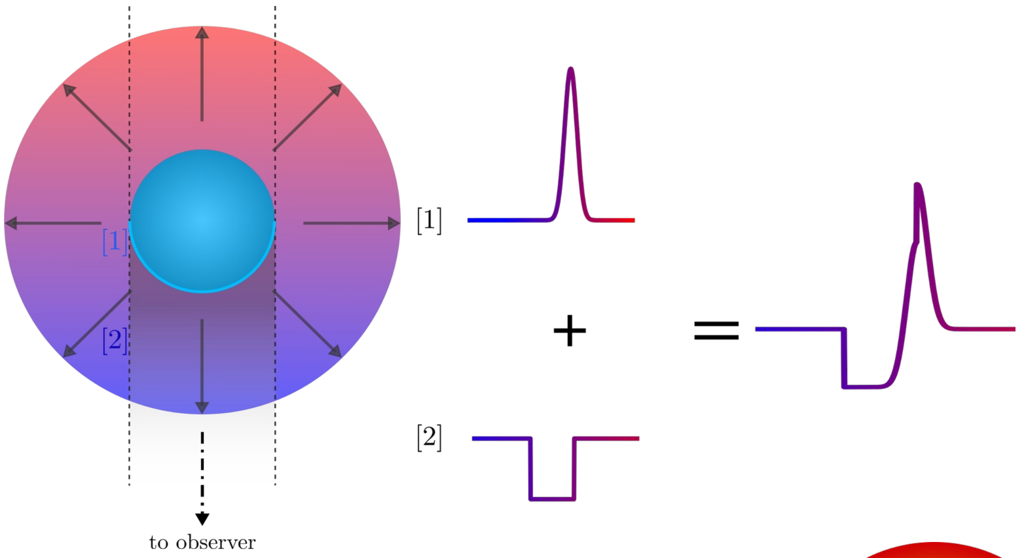
VLT/X-Shooter capabilities



Diversity of lines: illuminated stellar wind

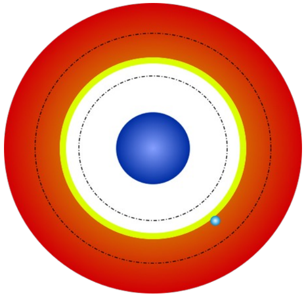
Hydrogen & Helium lines





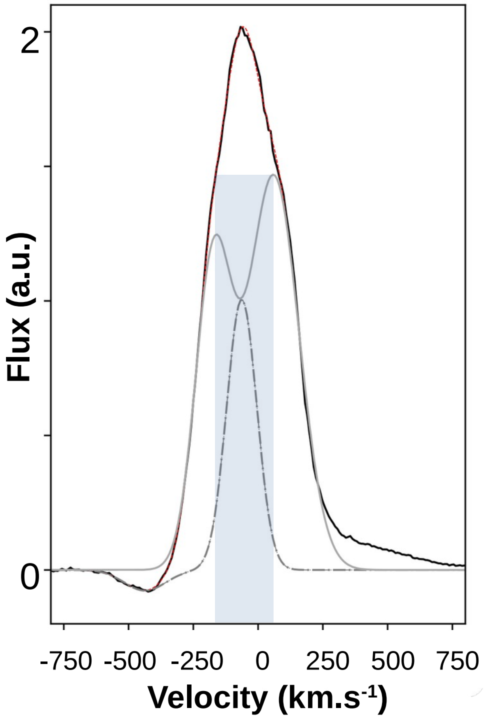
→ Equatorial wind

$V_{inf} = 340 – 370\ km.s^{-1}$

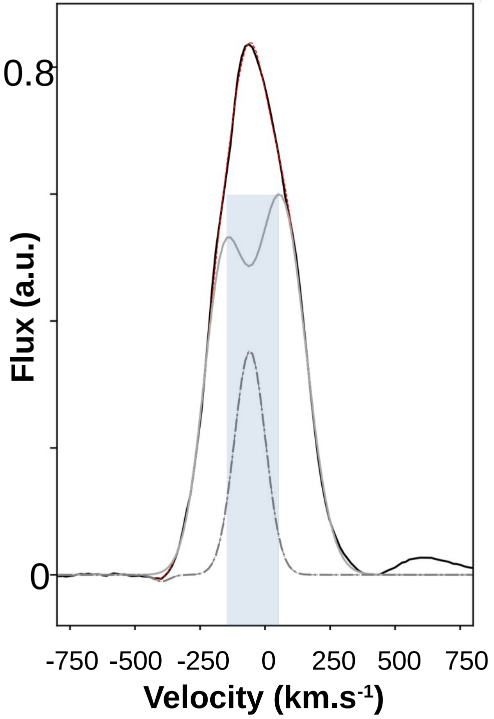


Diversity of lines: evidence of inner rim

The strongest (and cleanest) HI lines



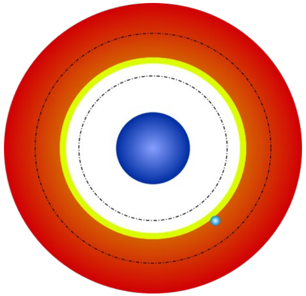
Brγ 2.16μm



HI 1.28μm

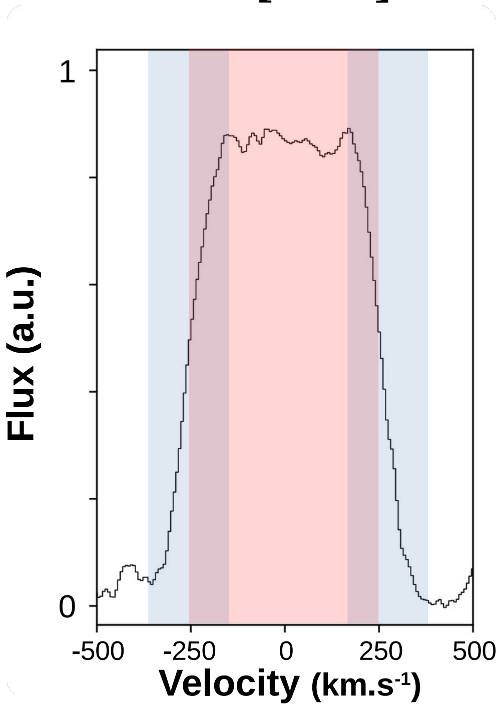
→ Associated to orbital motion of the inner rim :

V sin(i) = 113 +/- 4 km.s^{-1}

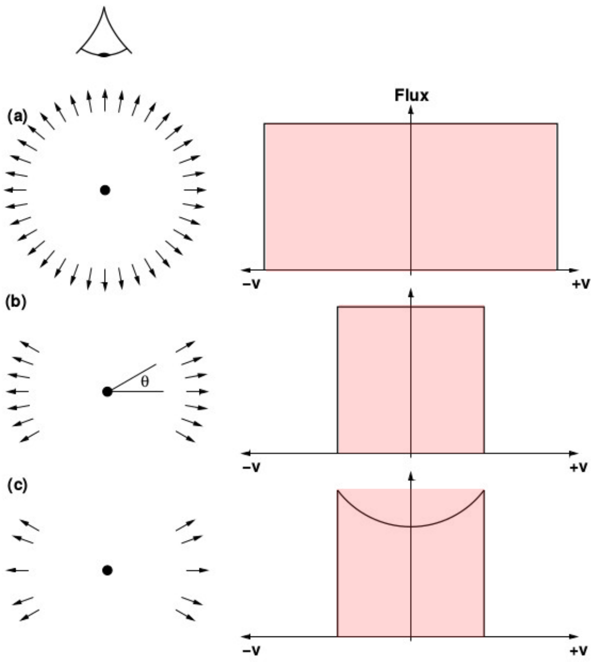


Diversity of lines: peculiar disk wind

FeII & [FeII] : Flat-topped profiles



FeII in IGR J16318-4848



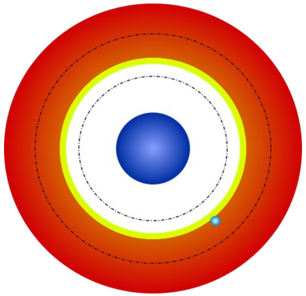
Bertout & Magnan 1987, Hynes+2002

Spherical expansion

$V_{inf} = 250 \pm 20$ km.s^{-1}

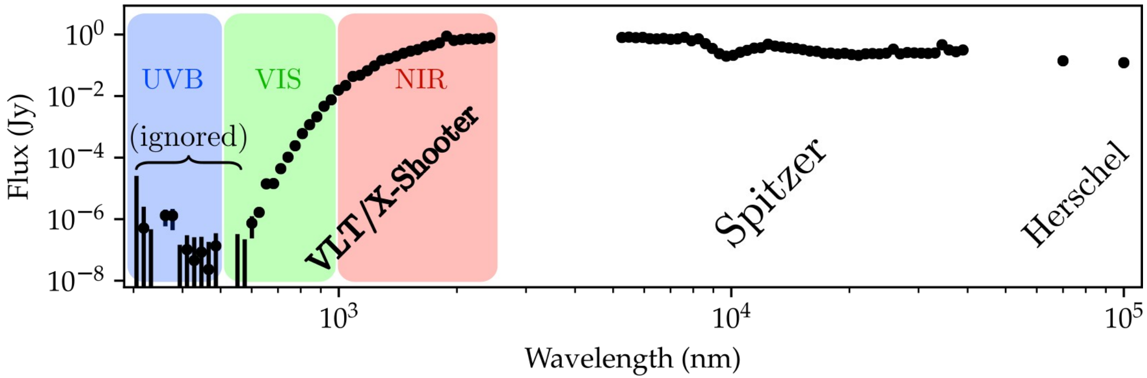
Orbital motion ?

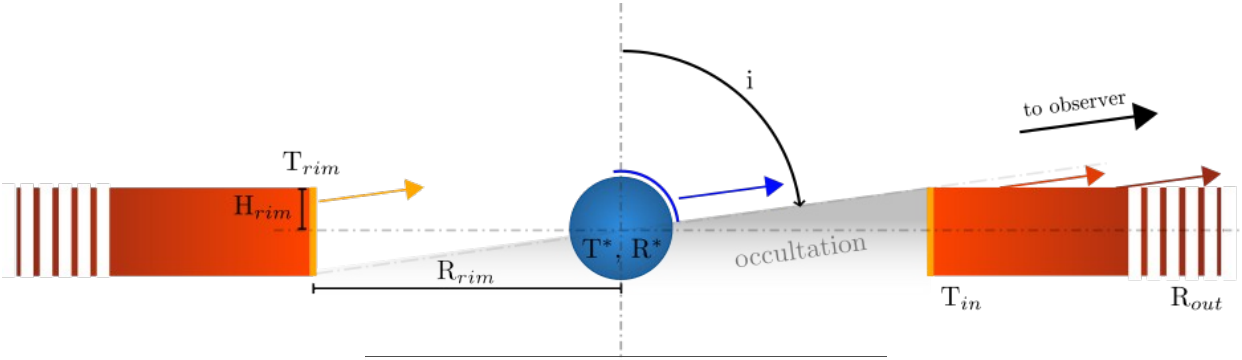
$V_{orb} = 80 \pm 20$ km.s^{-1}



Broadband spectral energy distribution

X-Shooter + Spitzer + Herschel





Adopted geometry

Star, Rim :

blackbodies

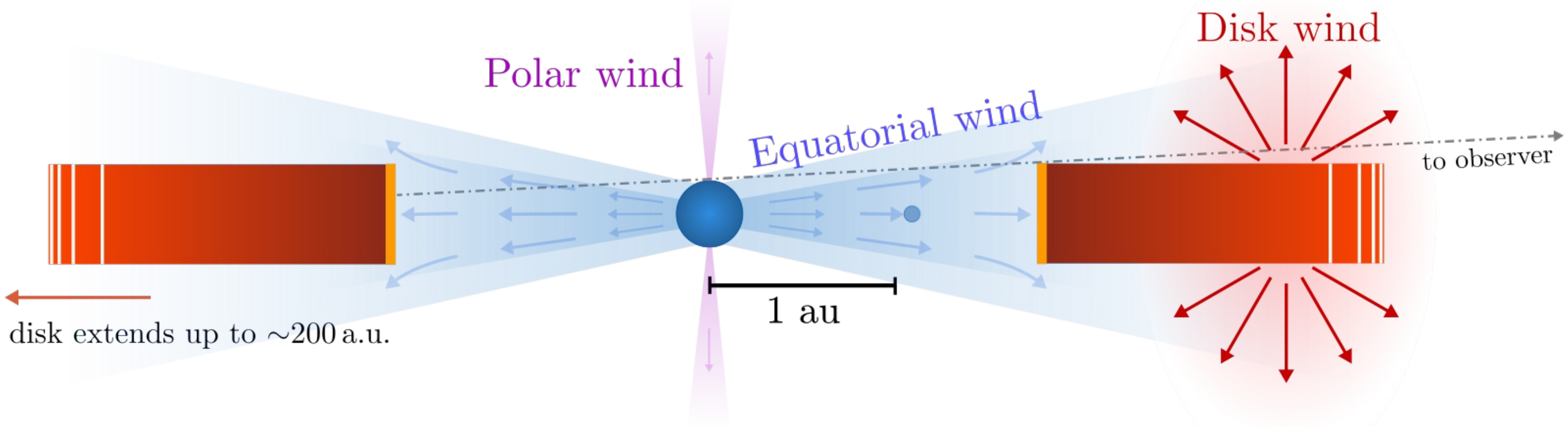
Disk : multi-T

blackbody

$$T_{disk}(r) = T_{in}\left(\frac{r}{R_{in}}\right)^{-q}$$

Lachaume+2007

The final picture: IGR J16318's environment



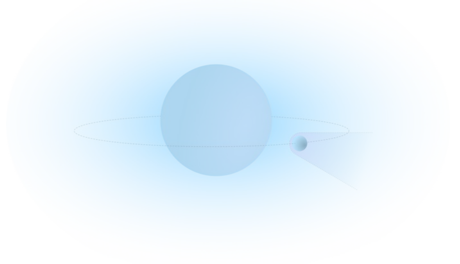
→ confirmed by stellar atmosphere & wind modeling (PoWR) !

- wind velocity
- inclination
- distance
- general geometry
- inner & outer disk
- accretor's orbit

- circumbinary material: where does it come from ?
- polar wind ?
- accretor: NS ? BH ?

Observing the history of binary star systems

I – The most obscured supergiant HMXB in the Galaxy



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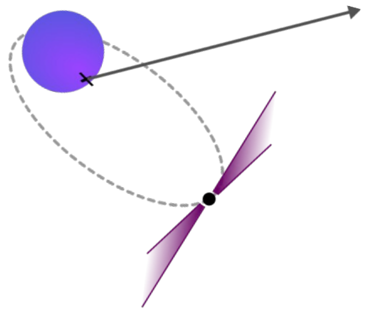


III – Finding the birthplace of stellar systems

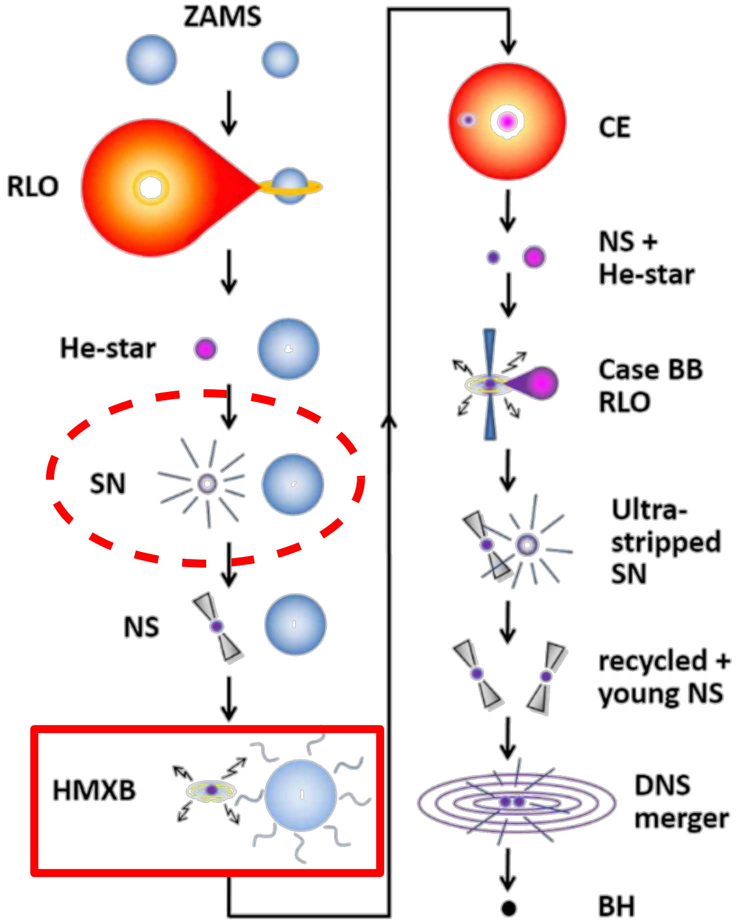
Evolution of High-Mass X-ray Binaries

Supernova event associated with the formation of the compact object

→ explosion = mass loss + asymmetry

Orbital parameters govern how binaries will evolve

Survival rate ?
Impact on orbit ?



Tauris+2017

Pre-requisites

i) Build a list of HMXBs known in the Milky Way

- cross-match between old HMXB catalogue (Liu+2006) with current INTEGRAL sources (Bird+2016)

- cross-match with Simbad (Centre de Données astronomiques de Strasbourg)

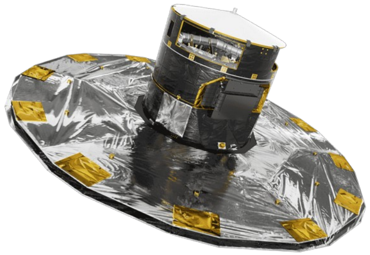
- some candidate HMXBs in previous catalogues are now confirmed/discarded

- retrieve exact references for spectral type, mass, period, eccentricity, radial velocity (1D)

ii) Find the Gaia counterparts of those HMXBs & retrieve position (3D) and proper motion (2D)

→ 6D data (position + proper motion + radial velocity)

Peculiar Velocity = Velocity – Galactic orbital motion



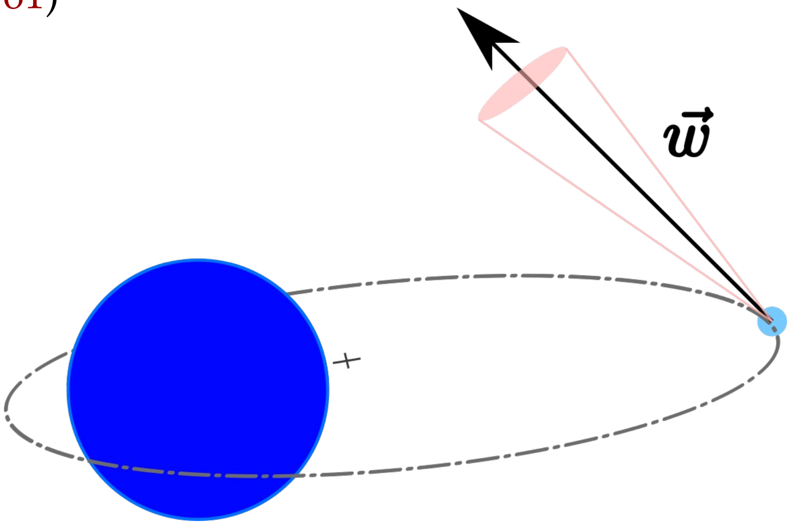
Deriving neutron star kicks

Analytical equation linking pre-SN to post-SN orbital parameters (Kalogera 1996), assuming an **isotropic probability of the kick direction**.

- Blaauw kick (spherically symmetric mass loss, Blaauw 1961)
- Asymmetric kick (random direction)

Hypotheses:

- circularized systems Dosopoulou & Kalogera 2016
- fixed NS mass @ 1.4M_{Sun} Kiziltan+2013
- companion is unaffected by the supernova Liu+2015



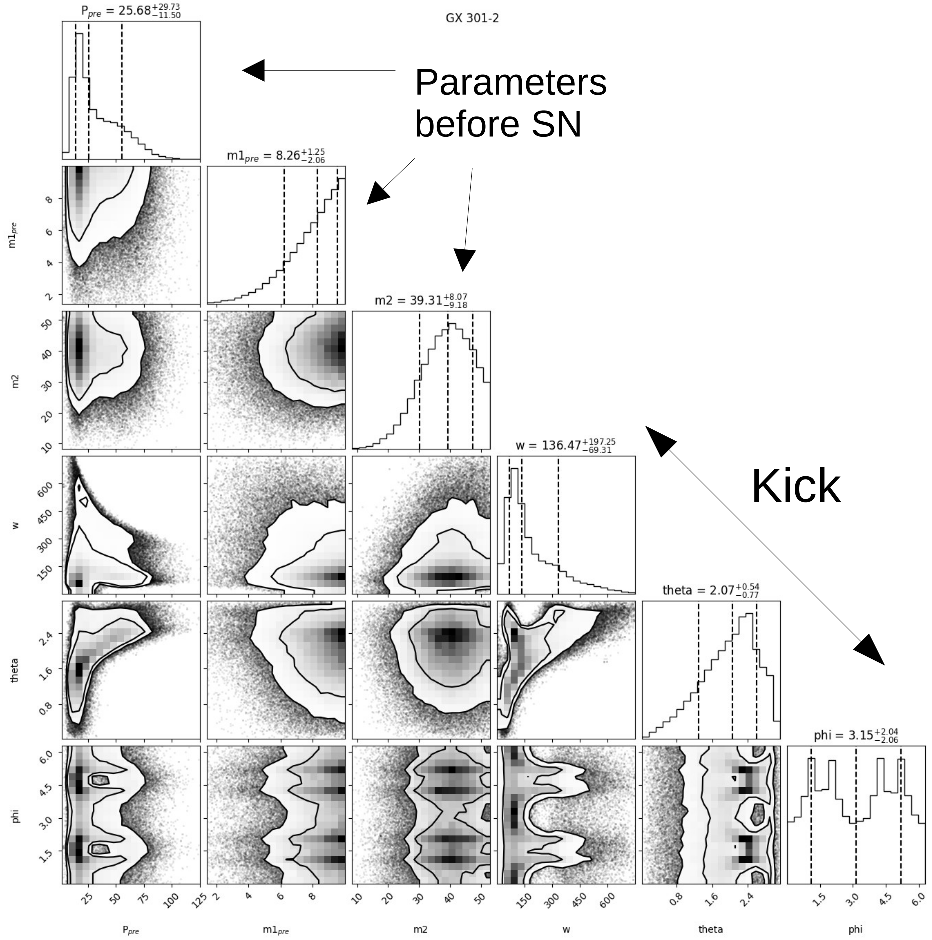
Deriving neutron star kicks

Bayesian approach:

- Priors on kick magnitude, initial P_{orb} and pre-SN mass

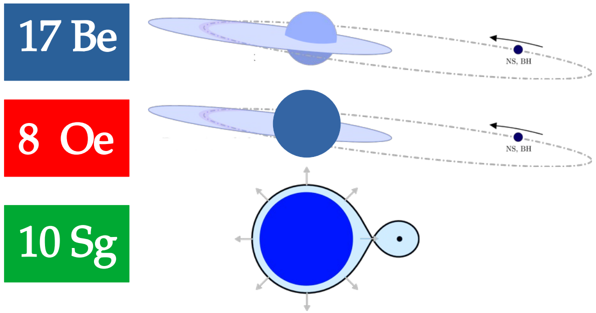
- Likelyhoods: Gaia observables, companion mass, P_{orb} & eccentricity

→ Explore the posterior distributions using Markov Chain Monte Carlo (MCMC)



Results on kick distributions

Inferred kick magnitudes on 35 HMXB :

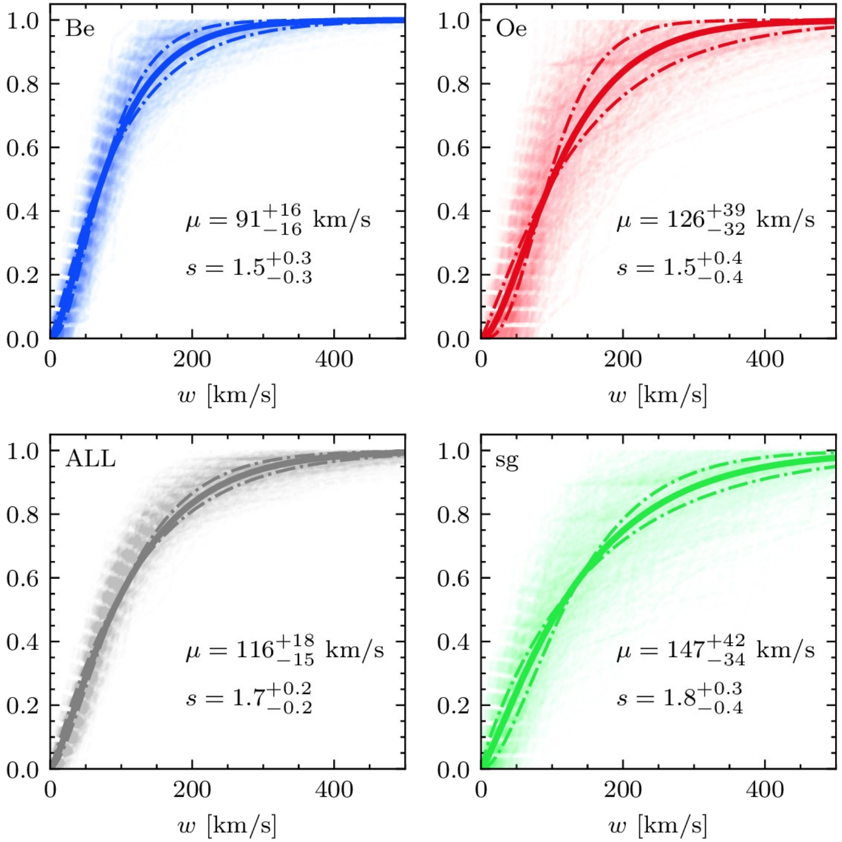


→ Kicks are reproduced with Gamma functions

→ More low-kick contribution

Disrupted systems, stripped progenitors…

Cumulative distributions of kicks



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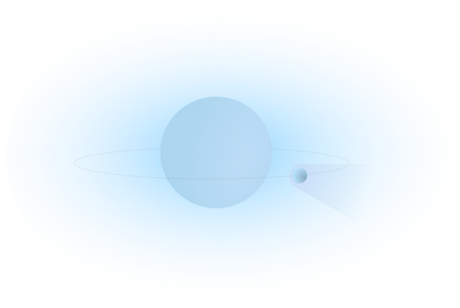

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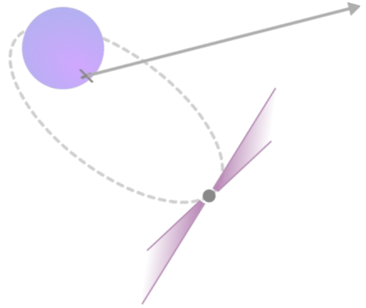
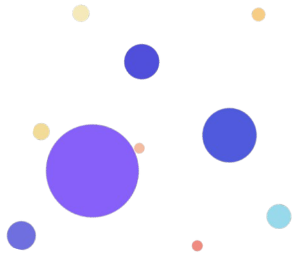


III – Finding the birthplace of stellar systems



Natal kick & migration from birth site

Supernova event = neutron star (or black hole) **natal kick.**

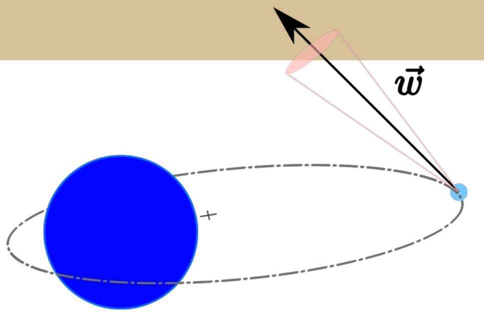
→ impact on orbital parameters (P_{orb}, eccentricity)

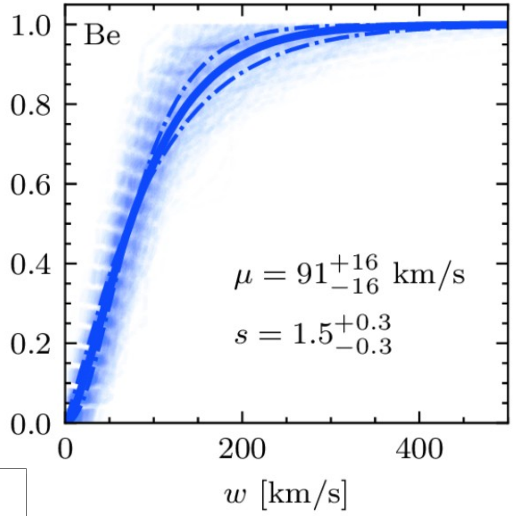
→ survivability (large kick → unbound system ?)

→ imprint on the peculiar velocity of the whole system

Order of magnitude : Vpec ~100 km/s → migration of ~ 100 pc/Myr

Even if HMXBs are young (few dozen Myr), migration distance can be high.





Fortin et al. 2022b

Birthplace of HMXBs and Galactic ecology

- Galactic structures susceptible of hosting massive star formation :

  young open clusters, spiral arms, isolated ?

Questions

How do HMXBs fit in the Galactic ecology ?

Are there correlations between formation scenarios and the nature of HMXBs ?

What we get

Infer the age of HMXBs since the first supernova event

→ evolution timescales, formation scenarios, history...

Correlation between spiral arms and/or OB associations in Milky Way : Bodaghee+2012, Coleiro+2013

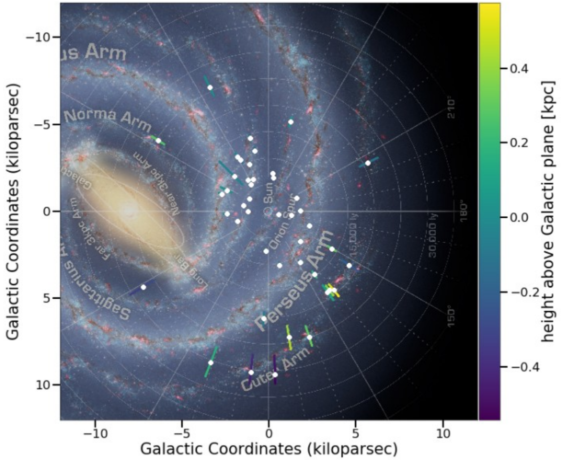
→ Need accurate kinematical data !

Astrometry from Gaia EDR3

High-Mass X-ray Binaries

Fortin+2022b

- 94 confirmed in Milky Way
- 80 observed by Gaia
- **26 with full 6-D astrometry**

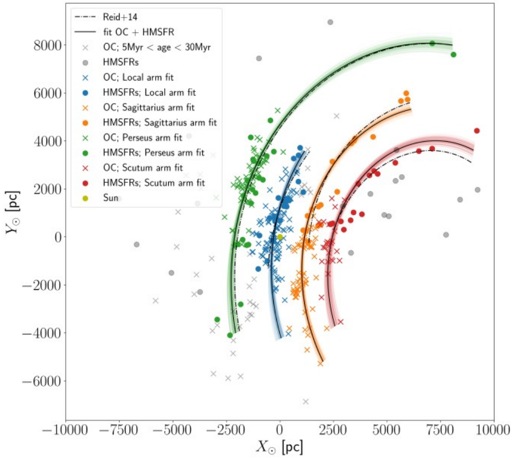


Galactic spiral arms

Castro-Ginard+2021

- Local, Sagittarius, Perseus, Scutum
- shape + motion

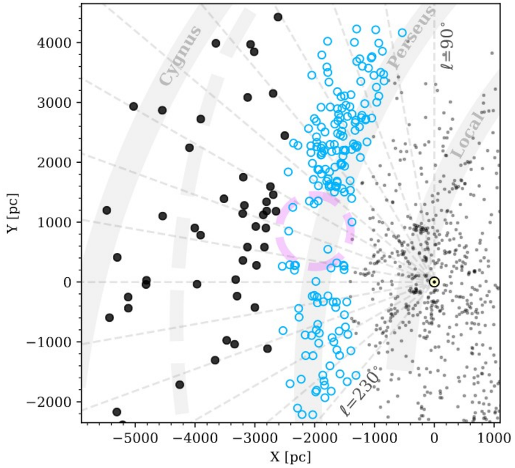
$$\ln \frac{R_G}{R_{G,ref}} = -(\theta_G - \theta_{G,ref}) \tan \psi$$



Open stellar clusters

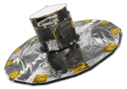
Cantat-Gaudin+2020

- 2017 within ~5kpc
- age from HR isochrone fitting
- **1381 with full 6-D astrometry**



Integration of orbit around the Milky Way

- Use of python module *Galpy* to initialize & integrate the motion of HMXBs and clusters
- MWPotential2014 (Bovy 2015) : bulge + disk + dark matter halo
- 500 timesteps of 0.2 Myr → explore the orbits until 100 Myr ago



Gaia astrometry is very accurate ! ... but not perfect :(

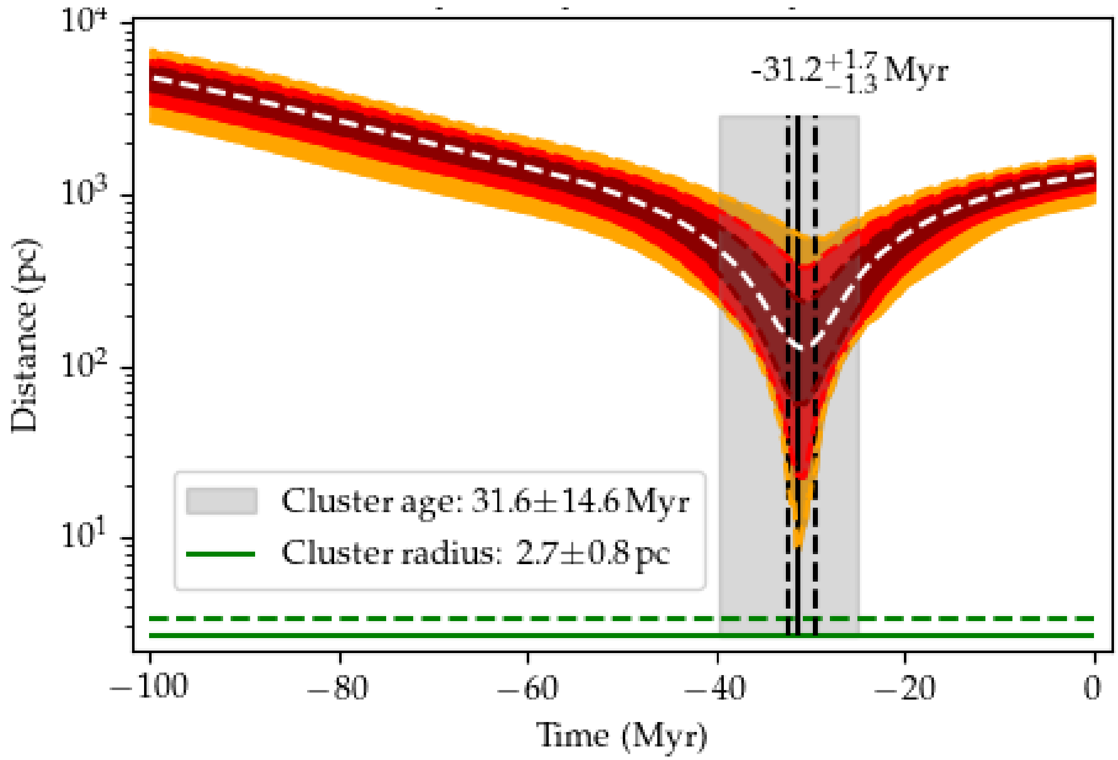
→ 1000 orbit integrations using initial parameters drawn from distributions according to Gaia data

- We obtain, for each timestep, a distribution of possible positions & velocities

→ Compute the possible distances to clusters and spiral arms to find **encounter candidates.**

→ simple galactic potential, low sample size → not too CPU-intensive

Encounter detection : time-distance histograms

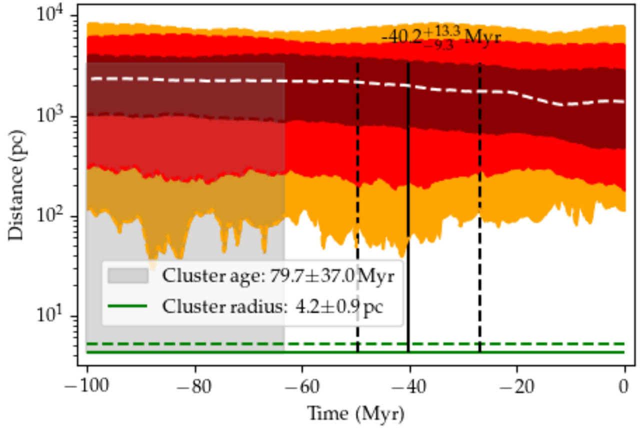


Encounter detection : validity of the method

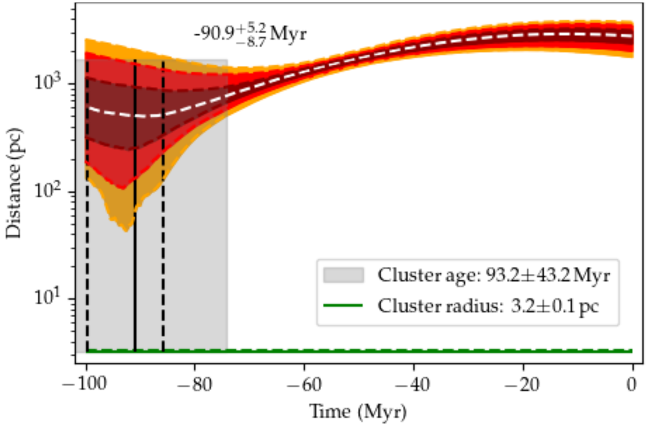
→ Simulations over randomly generated HMXBs and clusters to test the ability to find a birthplace

- chose a random birth date in [1 : 100] Myr
- initialize a birth cluster at a random position + velocity
- initialize HMXB born somewhere near the cluster
- apply random natal kick to HMXB
- integrate both orbits up until today
- generate dummy Gaia astrometry for HMXB & cluster of random quality (according to real data)
- look for an encounter

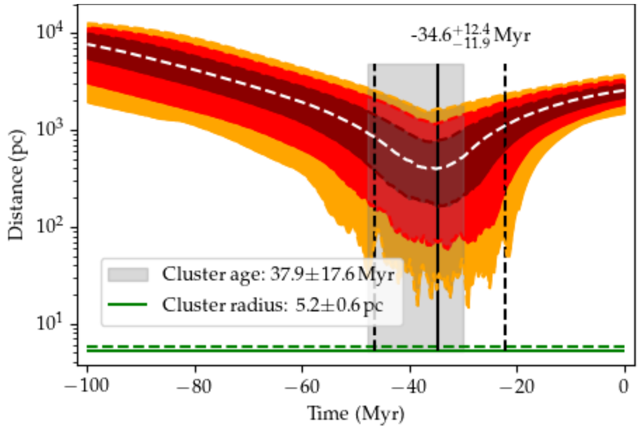
Encounter detection : validity of the method



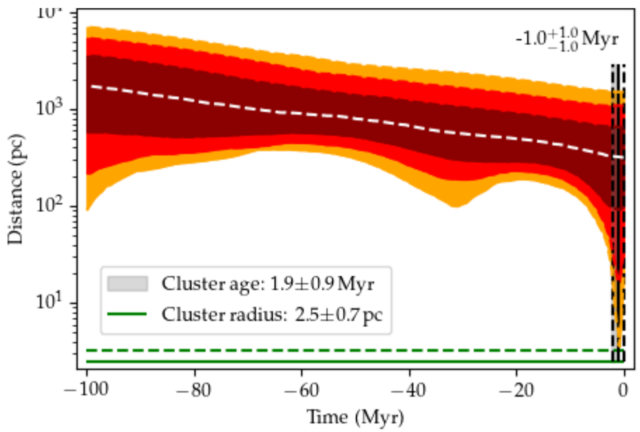
← Bad astrometry : 10% failed cases



Good astrometry →
retrieve old encounters



produce both sharp →
← and wide distributions



General results – Birthplace statistics

Open Cluster	tSN [Myr]
1A 0114+650	4.4
LS I+61 303	15
X Per	24
HD 259440	38
4U 1700-377	1.9
IGR J17544-2619	5.4
Cyg X-1	4.4
7	

Spiral arm	tSN [Myr]
1A 0535+262	18
2FGL J1019.0-5856	10
Cen X-3	1.9
1E 1145.1-6141	25
4U 1538-522	10
IGR J18450-0435	20
SS 433	<60
4U 2206+543	25
8	

Isolated ?
IGR J00370+6122
IGR J08408-4503
Vela X-1
GX 301-2
PSR B1259-63
LS 5039
MWC 656
7

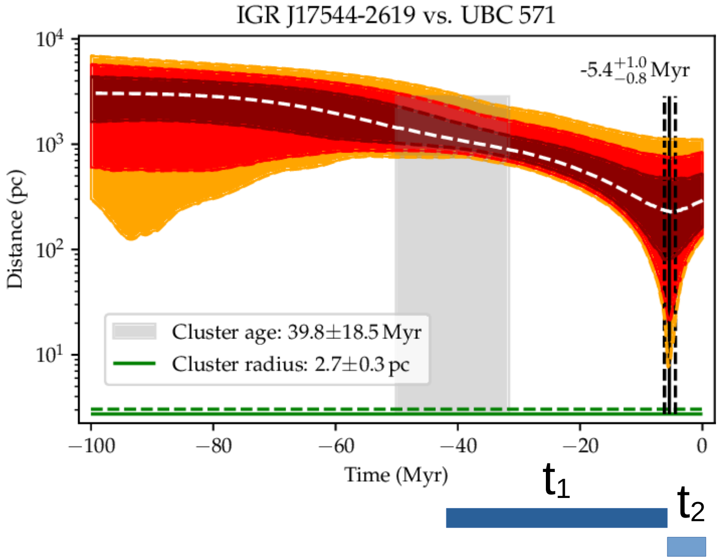
- HMXBs can have encounters with both clusters and spiral arms

→ degeneracy is always lifted when taking into account companion mass & evolution timescales

Actual results : ZAMS masses, and more

Mass – Age relation for massive stars (10 – 60 M⊙) : $\frac{M}{M_\odot} = \left[10^{-4}\left(\frac{t_{ZAMS}}{Myr}\right)\right]^{\frac{1}{1-\alpha}}$; $\alpha = 3.125$ (Figueiredo+1991)

Cluster encounters give primary star lifetime (**t_1**) and age since supernova (**t_2**) :



$t_1 \rightarrow M_{1,i} = 14.4$ +/- 0.2 M⊙ — Primary ZAMS mass

$t_1 + t_2 \rightarrow M_{2,i} \leqslant 13.5$ +/- 1.8 M⊙ — Secondary ZAMS mass (upper limit)

$M_{2,f} = 23$ M⊙ $\rightarrow M_{acc} \geqslant 9.5$ M⊙ — Initial mass transfer (lower limit)

$M_{1,\text{ pre-SN}} \leqslant 4.9$ M⊙ — Pre-supernova mass (upper limit)

→ Binary evolution through kinematics

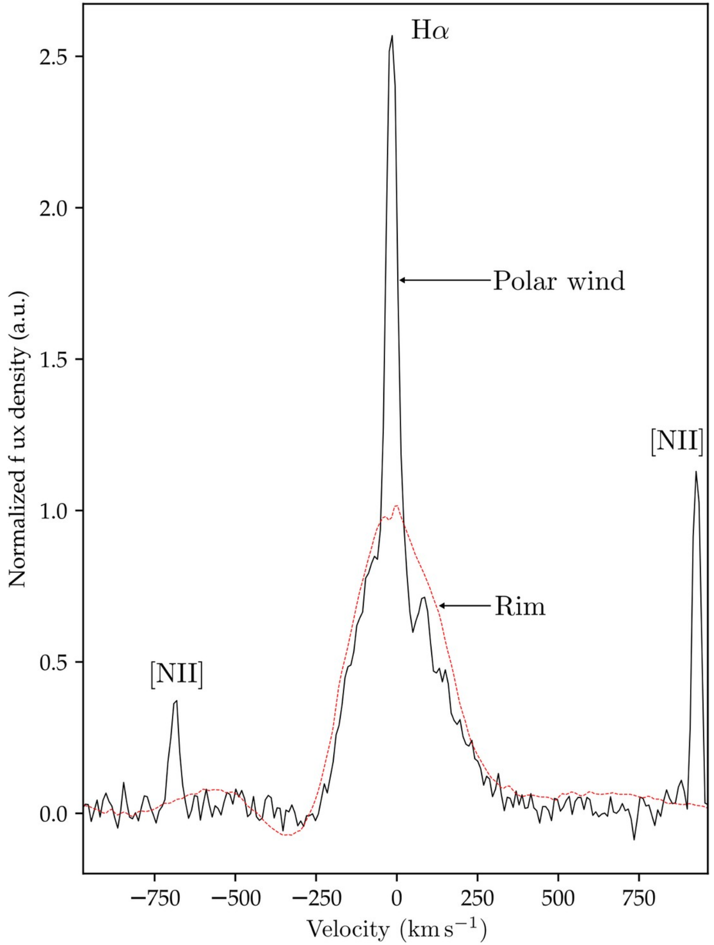
Conclusion & Prospects

- Binary stars are not uncommon (but still exotic !)
- X-ray binaries are challenging to observe → multi-wavelength
- We can observe their past using current optical/IR facilities (VLT, Gaia)
- Great synergy with other fields: supernovae, stellar winds...

- Next generation of observatories coming right now !
  LSST, SVOM, eRosita (?), and Athena later on
- Gravitational waves: probing the future of X-ray binaries
  LIGO/Virgo/KAGRA O4 coming on May 24th for 18 months,
  hopefully lots of neutron star merger events like 17/08/2017

Thanks for listening !

Extra: fast polar wind ?



- depolarization across Halpha line in sgB[e] rms 82 (Seriacopi+2017)

→ produced in a large volume around the star

- no sign of narrow features in other HI (disk rim)

- if polar wind, assume v ~ 1000 km.s-1

→ inclination angle is ~88°, otherwise we should see double-peaked line

Extra: distance to the binary

- Very absorbed → Gaia parallax poorly constrained (in all data releases)

- Bayesian inference to invert parallax from Bailer-Jones+2020: 5 +/- 3 kpc

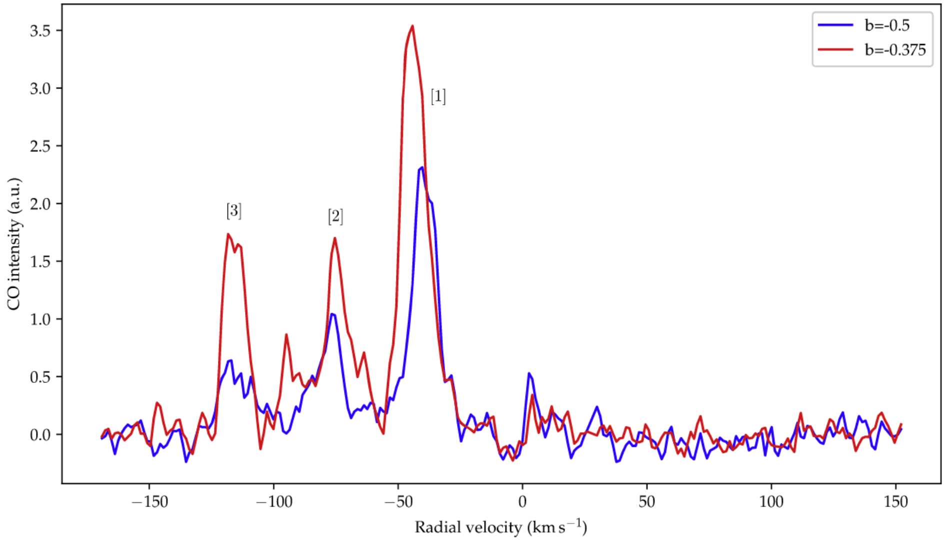
- Two star forming regions nearby at 2.4 and 4.9 kpc (Russeil 2003)

- Recovered their position in Galactic spiral arms from Dame+2001 by matching radial velocities

→ radial velocity of IGR J16318 is compatible with the SFR at 4.9 kpc.

→ incorporate this in Bayesian scheme & Gaia data:

D = 4.9 (+1.9 -1.5) kpc.



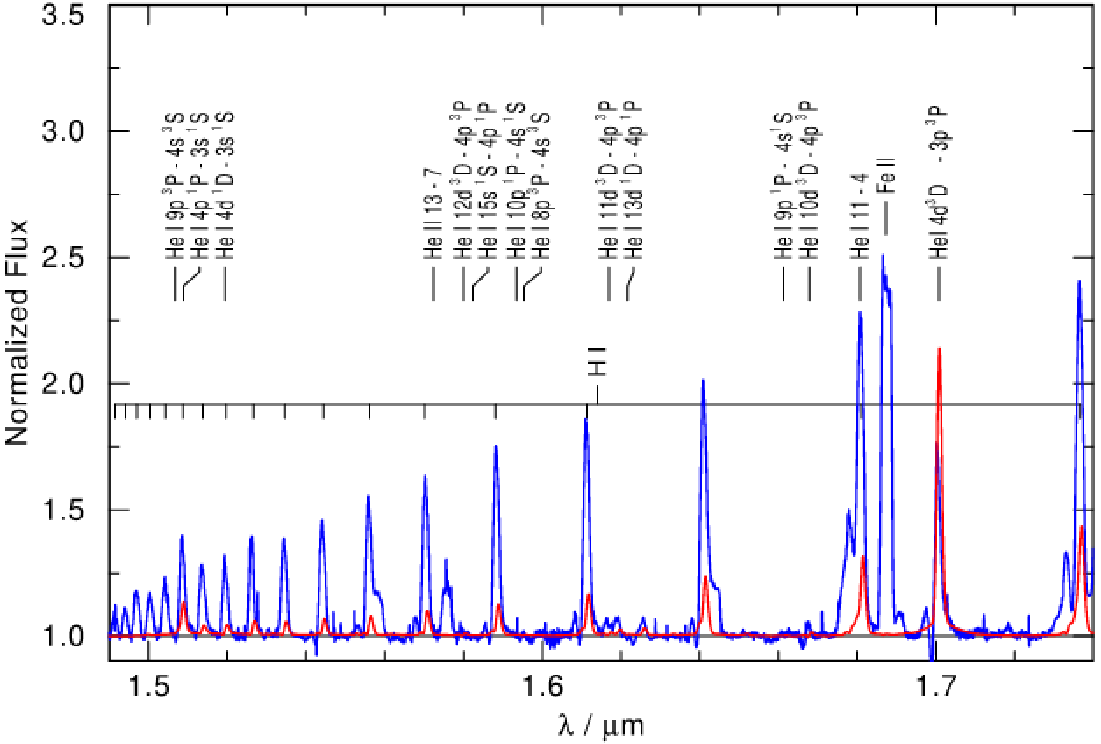
Extra: stellar atmosphere & wind modeling

PoWR code output compared to observed spectrum:

- HI lines barely reproduced
- good agreement with HeI lines
- same wind velocity (~400 km.s^{-1})

→ confirms HI mainly comes from rim

→ highly He-enhanced star ?



Disrupted systems, isolated NS velocities

Tauris & Takens 1998 : equations for velocity of a NS kicked-out of the binary after the SN event

Observed velocity distribution of isolated radio pulsars :

Hobbs+2005 → **265 km/s**

Igoshev 2020 → **230 km/s** (or 146 + 317 km/s)

We keep track of disrupted systems (5 to 50% of simulation outcomes depending on the binary)

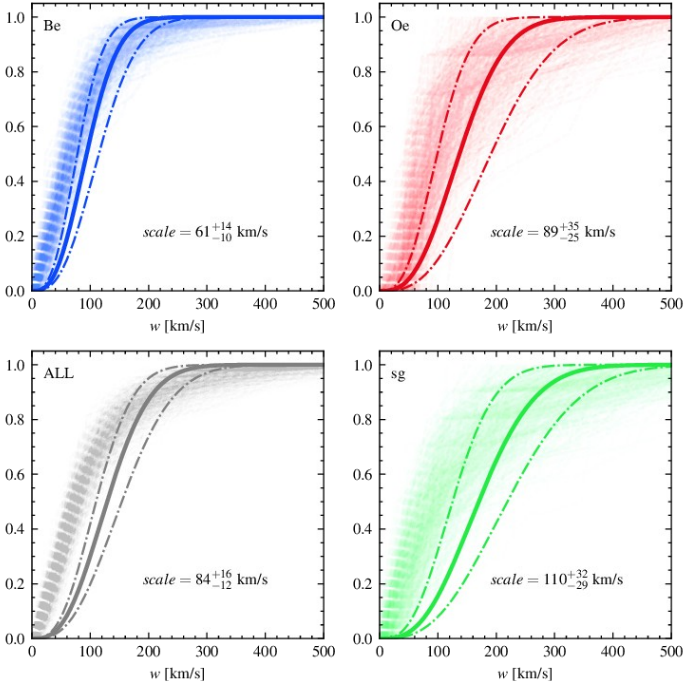
→ NS velocity from disrupted systems in our sample : **110 km/s**

→ In case of disruption, < 3% result in fast pulsars (> 500 km/s, large initial period > 1000 d required)

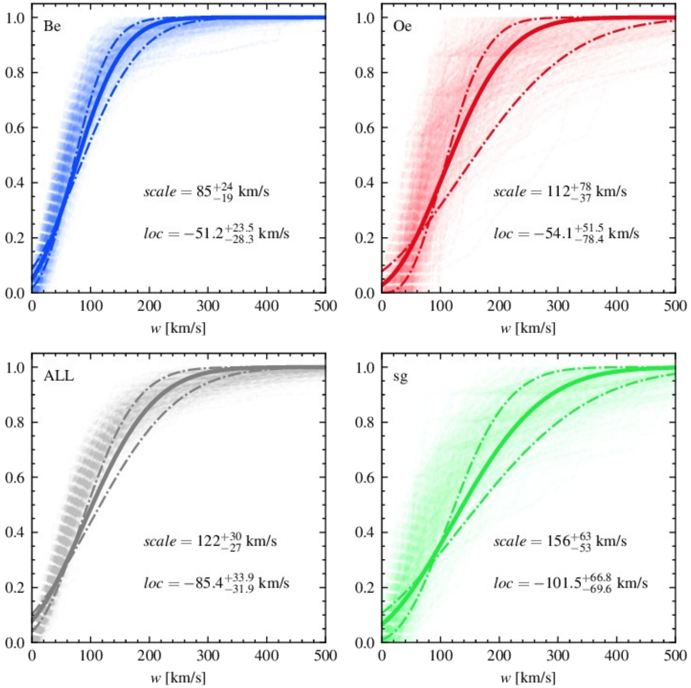
→ Binary evolution unlikely to be a formation channel for fast isolated NS.

Extra: Maxwellian vs. Gamma

Maxwellian is historically used to model kicks in isolated pulsars (Hobbs+2005, Ng & Romani 2007, Noutsos+2013)



Classical Maxwellian



Shifted Maxwellian

Unbound systems ?

→ observed vs. pop synth.

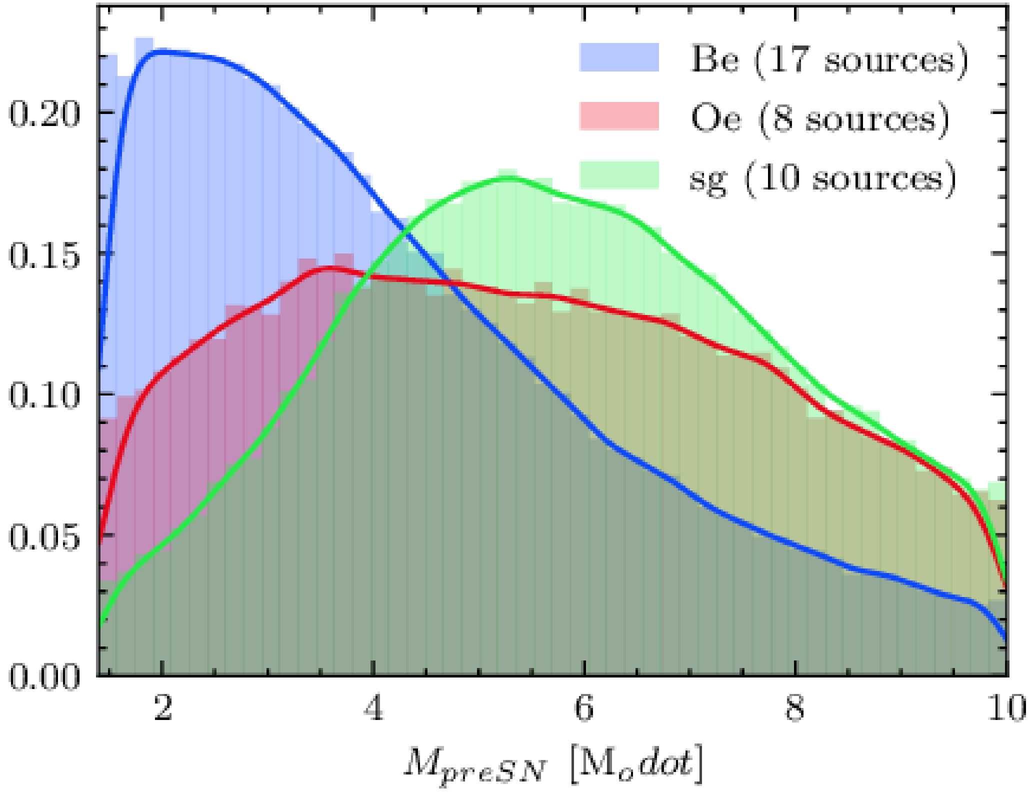
Stripped progenitors ?

→ lower pre-SN mass

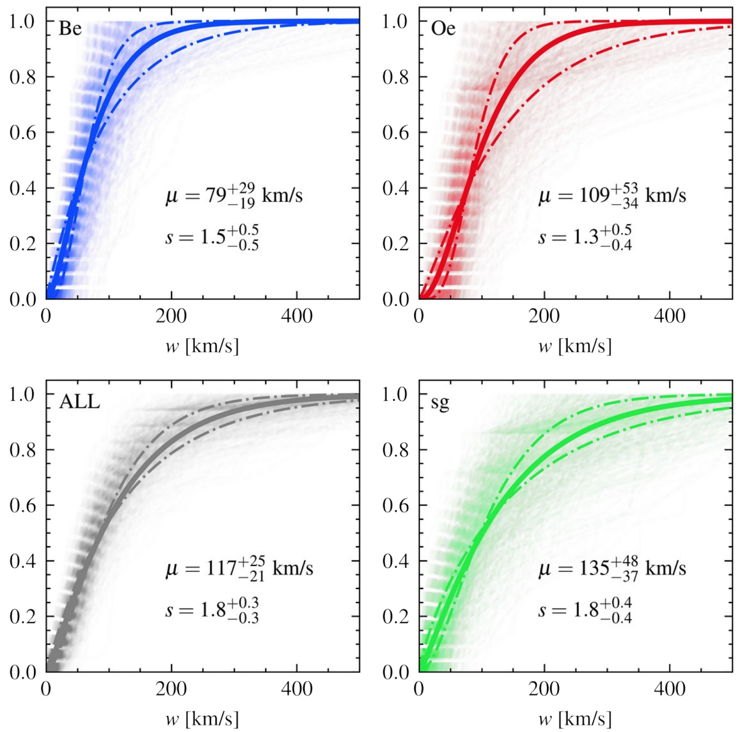
Kick isotropy ?

→ NS spin axis

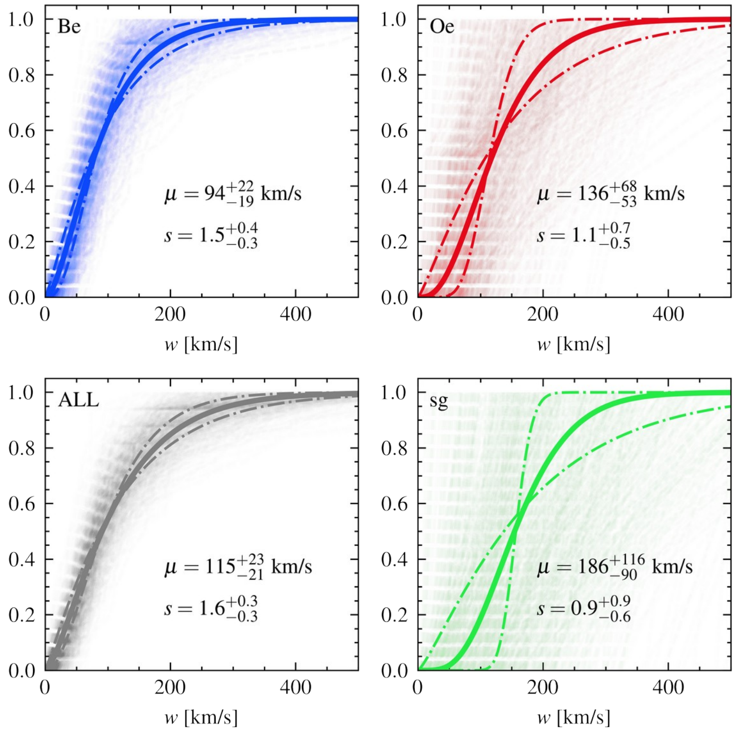
Extra: $M_{pre\text{-}SN}$ distribution



Extra: impact of missing radial velocity



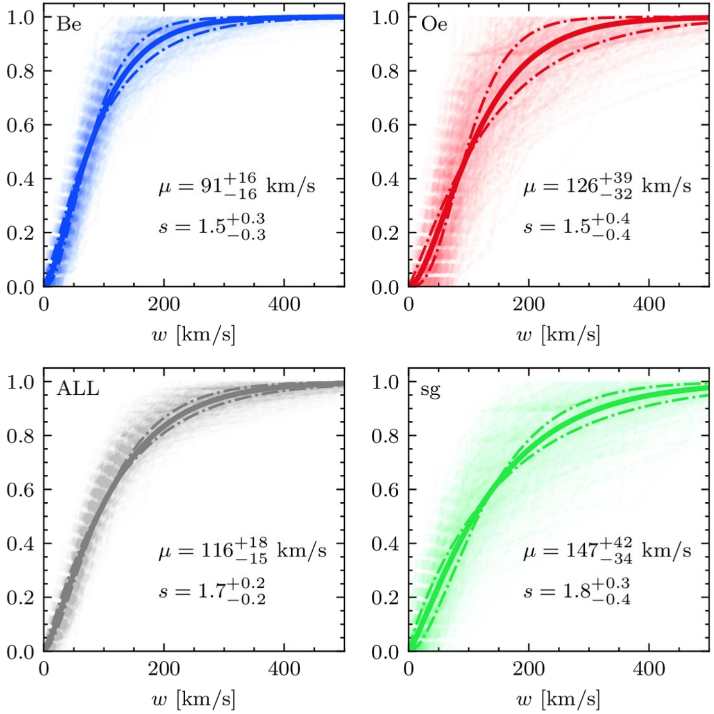
With RV only



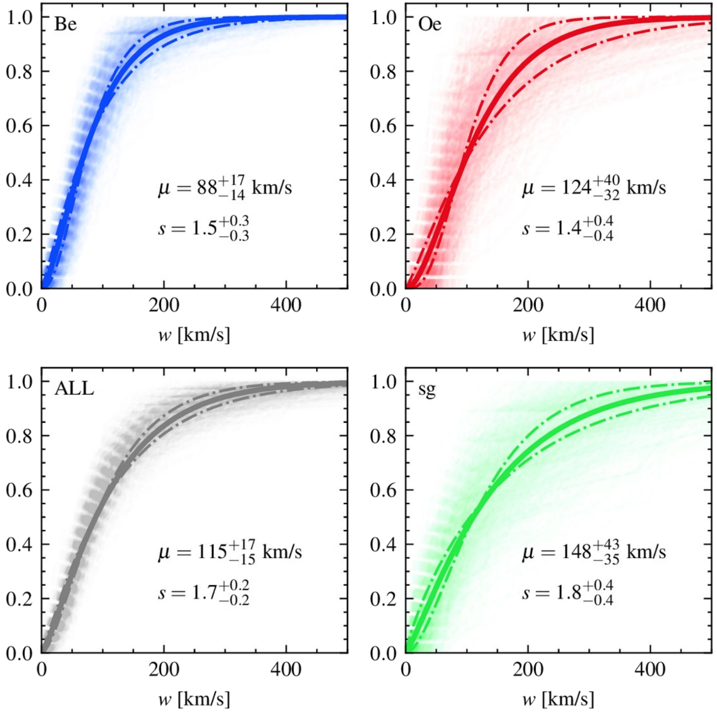
Without RV only

Extra: impact of neutron star mass

→ Assumed constant NS mass of 1.4 Msun, what about more massive NSs ?



$M_{NS} = 1.4\ M_{Sun}$



$M_{NS} = 1.8\ M_{Sun}$

No notable difference on the fitted parameters

→ NS mass variation are much smaller than $M_{pre\text{-}SN}$ uncertainty

Extra: building the list of HMXBs

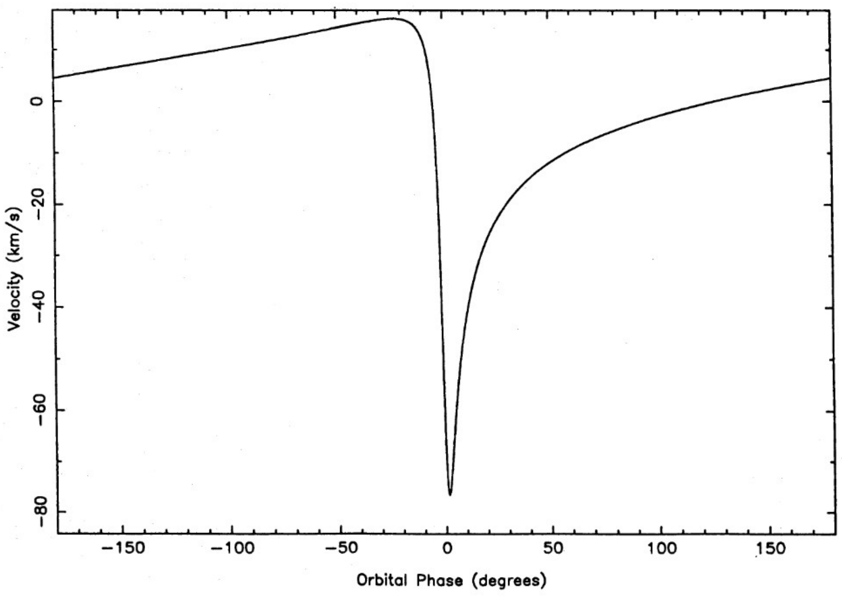
Example: PSR B1259-63

Radial velocity followup of the Oe companion star

→ Curve is presented but no value of the systemic velocity is given in the paper !

→ WebPlotDigitizer: we retrieved the data from the plot and fitted the systemic velocity

→ Do that for 130 HMXBs in the Galaxy.



Radial velocity of PSR B1259-63 (Johnston+1994)

Galactic distribution of Gaia clusters & HMXBs

- Gaia parallax → distances ≲ 5kpc

→ drastic decrease in known clusters with distance